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Can distributed generation offer substantial benefits in a Northeastern American context? A case study of small-scale renewable technologies using a life cycle methodology

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ABSTRACT

Renewable distributed electricity generation can play a significant role in meeting today's energy policy goals, such as reducing greenhouse gas emissions, improving energy security, while adding supply to meet increasing energy demand. However, the exact potential benefits are still a matter of debate. The objective of this study is to evaluate the life cycle implications (environmental, economic and energy) of distributed generation (DG) technologies. A complementary objective is to compare the life cycle implications of DG technologies with the centralized electricity production representing the Northeastern American context. Environmental and energy implications are modeled according to the recommendations in the ISO 14040 standard and this, using different indicators: Human Health; Ecosystem Quality; Climate Change; Resources and Non-Renewable Energy Payback Ratio. Distinctly, economic implications are modeled using conventional life cycle costing. DG technologies include two types of grid-connected photovoltaic panels (3 kWp mono-crystalline and poly-crystalline) and three types of micro-wind turbines (1, 10 and 30 kW) modeled for average, below average and above average climatic conditions in the province of Quebec (Canada). A sensitivity analysis was also performed using different scenarios of centralized energy systems based on average and marginal (short- and long-term) technology approaches. Results show the following. First, climatic conditions (i.e., geographic location) have a significant effect on the results for the environmental, economic and energy indicators. More specifically, it was shown that the 30 kW micro-wind turbine is the best technology for above average conditions, while 3 kWp poly-crystalline photovoltaic panels are preferable for below average conditions. Second, the assessed DG technologies do not show benefits in comparison to the centralized Quebec grid mix (average technology approach). On the other hand, the 30 kW micro-wind turbine shows a potential benefit as long as the Northeastern American electricity market is considered (i.e., oil and coal centralized technologies are affected for the short- and long-term marginal scenarios, respectively). Photovoltaic panels could also become more competitive if the acquisition cost decreased. In conclusion, DG utilization will represent an improvement over centralized electricity production in a Northeastern American context, with respect to the environmental, energy and economic indicators assessed, and under the appropriate conditions discussed (i.e., geographical locations and affected centralized electricity production scenarios).

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1. Introduction

Distributed generation from renewable technologies can play a significant role in meeting different energy policy goals, such as reducing greenhouse gas emissions, improving energy security, and adding supply to meet increasing energy demand [1–3]. These reasons explain why distributed generation is increasing in popularity [4] and has gained recent support such as the province of Quebec (Canada) [5].

Renewable energy production performances using small-scale technologies are still under continuous investigation [6]. Different impact categories have been studied, such as technico-economic impacts [7,8], global warming potential [9], land use [10] and cumulative energy demand [11]. However, only a few studies have combined all these different impacts through a life cycle perspective [6,12]. Furthermore, these identified studies focused on assessing ideal conditions and comparing small-scale renewable technologies to a high carbon centralized electricity production [4,7,13]. One major drawback of this approach is the difficulty in generalizing the results, due to the specific setting used to assess distributed generation. Therefore, it is recommended to perform a sensitivity analysis using different centralized energy systems to provide a better picture of the potential benefits of distributed generation as an energy policy [14,15]. The goals of this paper are summarized as follows:

- The first one consists in assessing the life cycle performance of small-scale renewable technologies (i.e. less than 50 kW). More specifically, the assessment integrates the environmental, economic and energy life cycle impacts of five commonly used small-scale systems: two types of grid-connected photovoltaic panels (3 kWp mono-crystalline and poly-crystalline system) and three types of micro-wind turbines (1 kW, 10 kW and 30 kW). Results were obtained for different climatic conditions prevailing in the province of Quebec (i.e. various levels of solar radiation and wind speed) to evaluate geographical dependencies.
- The second one consists of exploring the potential benefits and limitations of distributed generation in a Northeastern American context. A sensitivity analysis was performed characterizing different potentially affected centralized energy systems, based on average and marginal (short and long-term) values.

This article is structured as follows: Section 2 presents the small-scale renewable technology configurations and their energy output under different climatic conditions in the province of Quebec (Canada). Section 3 describes the proposed life cycle methodology and presents the results. Section 4 describes the possible affected centralized energy systems against which distributed generation can be assessed and presents the comparative results. All results are discussed in Section 5. Finally, Section 6 summarizes the conclusions drawn from the study.

2. Small-scale renewable technology configurations and energy analysis

This section presents the selected small-scale renewable systems and their energy output under different climatic conditions prevailing in the province of Quebec (Canada). Many configurations exist to produce renewable energy through small-scale grid-connected technologies. These configurations depend on many technical specifications such as photovoltaic panel types, micro-wind turbines power, inverter power and connection configurations. Keeping in mind the purpose of this study was not to assess all possible combinations, the most common configurations for a North American context were selected [16,17]. Table 1 shows the selected alternatives including their installation types.

Slanted roof mounting systems were selected because of the frequency of their installation [17]. Towers heights (10, 22 and 30 m) were chosen based on the power rate of the micro-wind turbines [16]. Essential components for the connection and the transmission of the produced energy, such as inverter (DC/AC) and electric cables, were also considered. The energy output of the micro-wind and photovoltaic systems was estimated via a data set of measured wind speeds and horizontal solar radiations (Table 2). These overall mean values were obtained using the long-term site averages for the province of Quebec [21]. Technical specifications of the selected small-scale systems were used to compute the final energy yield. Table 3 presents the annual energy output. The produced energy considers the performance of the inverter including all the necessarily connections and efficiencies (93.5% [17]) and the height of different wind towers (i.e. 10, 22 and 30 m). Table 3 shows that below average conditions, micro-wind capacity factor (CF) ranges between 3.3 and 7.8%. This is consistent with other reported values [4]. For average and above average conditions, micro-wind CF values are similar to those obtained

Table 1
Overview of the selected small-scale renewable technologies (solar photovoltaic and wind).

Technology	Type of installation	Power rate	Lifetime (years)	Reference
Mono-crystalline (mc)	Mounted-slanted roof	3 kWp	30	[17]
Poly-crystalline (pc)	Mounted-slanted roof	3 kWp	30	[17]
Micro-wind	Guyed pipe tower (10 m)	1 kW	20	[18,19]
	Lattice tower (30 m)	10 kW	20	[18,19]
	Non-guyed tubular tower (22 m)	30 kW	20	[20]

Table 2
Wind speeds and horizontal solar radiation ranges for the province of Quebec [21].

Parameters[a]	Conditions with respect to average		
	Below	Average	Above
Wind speed (m/s)	3.5	5.6	7
Horizontal solar radiations (kWh/m^2/year)	1067	1230	1387

[a] Measured at 10 m (adjustments are made for towers of different heights).

for a commercial wind farm [4]. The CF values for photovoltaic systems are also in agreement with typical values (Table 3) [1].

3. Life cycle performance methodology and results

Fig. 1 presents the applied methodology to assess the life cycle performance of the selected systems. Sections 3.1–3.3 describe in more detail each method and provide the obtained results. Section 4 describes the methodology used to identify the affected centralized energy systems and presents the comparative results.

3.1. Life cycle assessment

Life cycle assessment (LCA) is a widely used and recognized tool for evaluating potential environmental impacts of a product or a service over its lifetime: from the extraction of resources to the end-of-life [1,2,22]. The LCA methodology of is standardized by the ISO 14040 [23] and the ISO 14044 [24]. The primary function of small-scale grid-connected technologies is the production and the transmission of electricity to the centralized grid. The functional unit (FU) is to provide 1 kWh during the reference year 2009. The modeled system boundaries cover all the life cycle stages ranging from the extraction of resources to the end-of-life (i.e. cradle to grave).

The three micro-wind turbines differ according to the power rate (1 kW, 10 kW and 30 kW) and the installation type (Table 1). The assumed lifetime of the moving and the fixed part are 20 and 40 years, respectively. The list of materials for the micro-wind turbine were obtained from the manufacturer [25] and completed with the ecoinvent database [20]. The complete production process from material production to the final micro-wind system assembly is well described in the ecoinvent report [20]. It is assumed that all micro-wind turbines including all components were produced in the US [16] and shipped to the province of Quebec, for the installation stage. The average distance is assumed to be 1500 km. The electric cables and inverters were also assumed to be produced in the US. As the assessed systems are considered new technologies, data on decommissioning are not available. Decommissioning activities are assumed to be the same as for the installation. Moreover, a lack of knowledge still concerns the end-of-life of the assessed systems. Neither environmental burdens nor credits have been considered for the metals parts recycling stage. This approach is described in the ecoinvent report [17,20]. The remaining part (i.e. not metallic) are assumed to be landfilled and their environmental burdens have been considered.

Inverter (DC/AC) and electric cables data were also obtained from the ecoinvent database [17]. Because of the absence of life cycle inventory data for commercially available 1 kW and 10 kW inverters, the ecoinvent data were scaled depending on the power rate. The electric cable data were also adapted following the tower height and scaled depending on the power rate of the assessed systems. For the scaling step, it was assumed that the list of materials was proportional to the power rate [26]. The considered lifetime of the inverters was 15 years. Thus, the needed inverters take into account the lifetime of the micro-wind and photovoltaic systems. Electric cable lifetime was considered to be equal to the lifetime of the assessed systems. Electric cable data do not represent a product average data, but rather an example of possible installation [17].

The two grid-connected photovoltaic systems differ following the panel types (mono-crystalline and poly-crystalline). The two systems have the same power rate and the same mounting type (Table 1). The assumed lifetime for the two systems including their mounting systems is 30 years. The complete production process from silica extraction to the final panel assembly is well described in the ecoinvent report [17]. Silicon solar cells were assumed to be produced in Germany and shipped by boat to the US for the photovoltaic panel production stage. Photovoltaic installation distances and end-of-life assumptions are similar to those for the micro-wind life cycle. SimaPro v7.1 software [27] was used as it is widely employed by LCA practitioners. It contains several impact assessment methods. The IMPACT 2002+ impact method was selected to carry out this study because it allows for midpoint and endpoint modeling [28]. Figs. 2 and 3 present the environmental impact results (i.e. IMPACT 2002+ endpoint categories). The results are discussed in Section 5.1. As aquatic acidification and aquatic eutrophication impact categories are not integrated into an endpoint category [28], Appendix A provides IMPACT 2002+ midpoint category results (Table 9).

3.2. Cumulative energy demand and life cycle costing

The cumulative energy demand (CED) is the amount of primary energy consumed during the life cycle of a product or a service [29,30]. The CED system boundaries are similar to those of the LCA (i.e. from extraction of resources to the end-of-life). Various CED impact assessment methods exist. They vary according to primary energy classification. CED impact method v1.05 described by ecoinvent was selected [31]. SimaPro v7.1 software was also used for the modeling step [27].

Even if the CED has been developed to simplify the LCA model [29], its simultaneous application is advisable as long as energy

Table 3
Annual energy output for the considered climatic conditions (W30: micro-wind 30 kW, W10: micro-wind 10 kW, W1: micro-wind 1 kW, PVm: 3 kWp mono-crystalline, PVp: 3 kWp poly-crystalline).

Technology	Power curve reference	Below		Average		Above	
		Output (kWh)	CF[a]	Output (kWh)	CF	Output (kWh)	CF
W30	[20]	8760	3.3%	52560	20%	52560	40%
W10	[18]	6865	7.8%	22756	26%	22756	38.7%
W1	[18]	650	7.4%	2314.1	26.4%	2314.1	40.6%
PVm	[17]	2742[b]	10.4%	3153	12%	3153	13.5%
PVp	[17]	2742[b]	10.4%	3153	12%	3153	13.5%

[a] CF: capacity factor is the energy output as a percentage of the theoretical maximum rated output.
[b] 3 kWp mono-crystalline (PVm) and 3 kWp poly-crystalline (PVp) have the same produced energy. The performance is implicitly included in the amount of panel per Wp (i.e. 21.4 m^2 and 22.8 m^2/3 kWp, respectively [17].

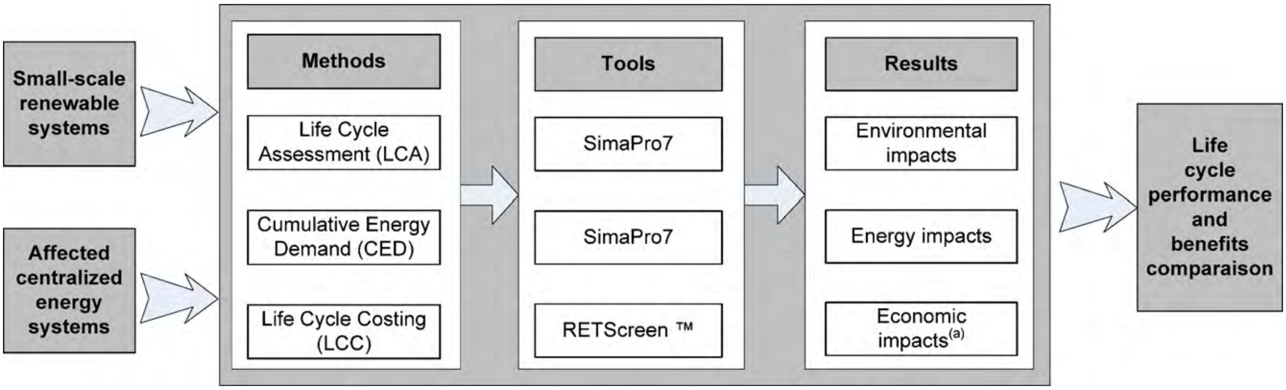

Fig. 1. Structure of the proposed methodology and interaction between the disciplines. [a]Economic impacts of the affected centralized energy systems were obtained following a literature review.

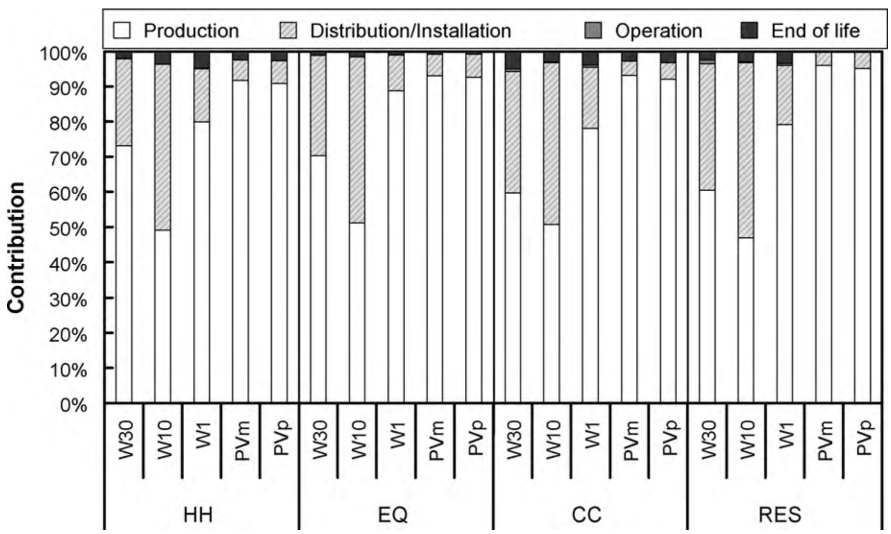

Fig. 2. Contribution analysis of LCA results by main stages (W30: micro-wind 30 kW, W10: micro-wind 10 kW, W1: micro-wind 1 kW, PVm: 3 kWp mono-crystalline, PVp: 3 kWp poly-crystalline, IMPACT 2002+ endpoint categories. HH: Human Health, EQ: Ecosystem Quality, CC: Climate Change, RES: Resources).

assessment is concerned. Indeed, LCA does not include an important indicator used in technical assessment of renewable technologies: the Energy Payback Ratio (EPR) [32,33]. The EPR is used as a performance indicator comparing the CED to the final energy produced. The latter depends on the technical specifications and configurations of the investigated technologies (Section 2). The Non-Renewable Energy Payback Ratio (NR-EPR) can also be used as a performance indicator, as it compares the cumulative non-renewable energy demand with the produced energy. This comparison is relevant for the assessment of renewable energy. Therefore, the NR-EPR is used to assess the studied systems. The results are presented in Fig. 3 and discussed in Section 5.1.

Besides environmental and energy assessments, the investigated systems are also compared using life cycle costing (LCC) methodology. As the results are used in parallel to environmental ones (i.e. LCA), there is no need to internalize the environmental impacts for the LCC modeling. Therefore, to avoid double counting, applying conventional LCC is justified [34]. As a basis for calculation, the economic impacts were scaled to the FU in LCA terms. Required data were obtained from the main manufacturers serving the subject area [18,35]. Some data were difficult to obtain as manufacturers are not always concerned by the whole life cycle process (e.g. do not necessarily install them and did not have full control of the final cost to the consumer). RETScreen user manual recommendations was used to fill data gaps especially for the installation, operation and end-of-life stages [21]. It was assumed that all production costs already accounted for transportation costs. In addition, as the end-of-life cost for small-scale systems was difficult to obtain, it was assumed that the decommissioning cost was equal to the installation cost and the landfilling cost. According to the LCA end-of-life assumptions (Section 3.1), the landfilling cost was estimated using the landfilled materials list (i.e. not metallic parts). Parameters of inflation, discount, and year of purchase were also considered in order to take into account the 'time value of money'. For these calculations, a discount rate of 6% was used and the inflation was approximated at 2% based on RETScreen user manual recommendations. The conventional LCC was computed using RETScreen software [21]. Table 4 summarizes

Table 4
Structure of the life cycle costs inventory[a] (W30: micro-wind 30 kW, W10: micro-wind 10 kW, W1: micro-wind 1 kW, PVm: 3 kWp mono-crystalline, PVp: 3 kWp poly-crystalline).

Systems	Production		Installation		Operation		End-of-life	
	Cost USD	%	Cost USD	%	Cost USD	%	Cost USD	%
W30	94486	58	32771	20	12746	8	22935	14
W10	47900	62	13629	18	5522	7	10418	13
W1	7414	67	1803	16	639	6	1280	11
PVm	11338	76	2288	15	0	0	1263	8
PVp	10420	76	2063	15	0	0	1139	8

[a] The life cycle inventory results were not normalized to the final energy produced.

Table 5
Alternative selection and geographical dependence (W30: micro-wind 30 kW; PVp: 3 kWp poly-crystalline; B.Avg.: below average; Avg.: average condition; A.Avg.: above average; HH: Human Health; EQ: Ecosystem Quality; CC: Climate Change; RES: Resources; NR-EPR: Non-Renewable Energy Payback Ratio).

	Wind speed conditions																	
	B.Avg.	Avg.	A.Avg	B.Avg.	Avg.	A.Avg	B.Avg.	Avg.	A.Avg	B.Avg.	Avg.	A.Avg	B.Avg.	Avg.	A.Avg	B.Avg.	Avg.	A.Avg
	HH			EQ			CC			RES			NR-EPR			Cost		
Solar radiation conditions																		
B.Avg.	PVp	PVp	W30	PVp	PVp	W30	PVp	W30	W30	PVp	W30	W30	PVp	W30	W30	PVp	W30	W30
Avg.	PVp	PVp	W30	PVp	PVp	W30	PVp	W30	W30	PVp	W30	W30	PVp	W30	W30	PVp	W30	W30
A.Avg.	PVp	PVp	W30	PVp	PVp	W30	PVp	W30	W30	PVp	W30	W30	PVp	W30	W30	PVp	W30	W30

the obtained life cycle cost inventory. The economic results are presented in Fig. 3 and discussed in Section 5.1.

3.3. Life cycle performance

Trade-offs are easier to make when several life cycle aspects are assessed separately. This section aims at comparing the studied systems to reduce their environmental and economic impacts while reaching a good energy performance. Table 5 provides the performing distributed generation alternatives considering the assessed climatic conditions.

Section 5.1 discusses the presented results and explains the dominance of micro-wind 30 kW and 3 kWp poly-crystalline on the studied systems.

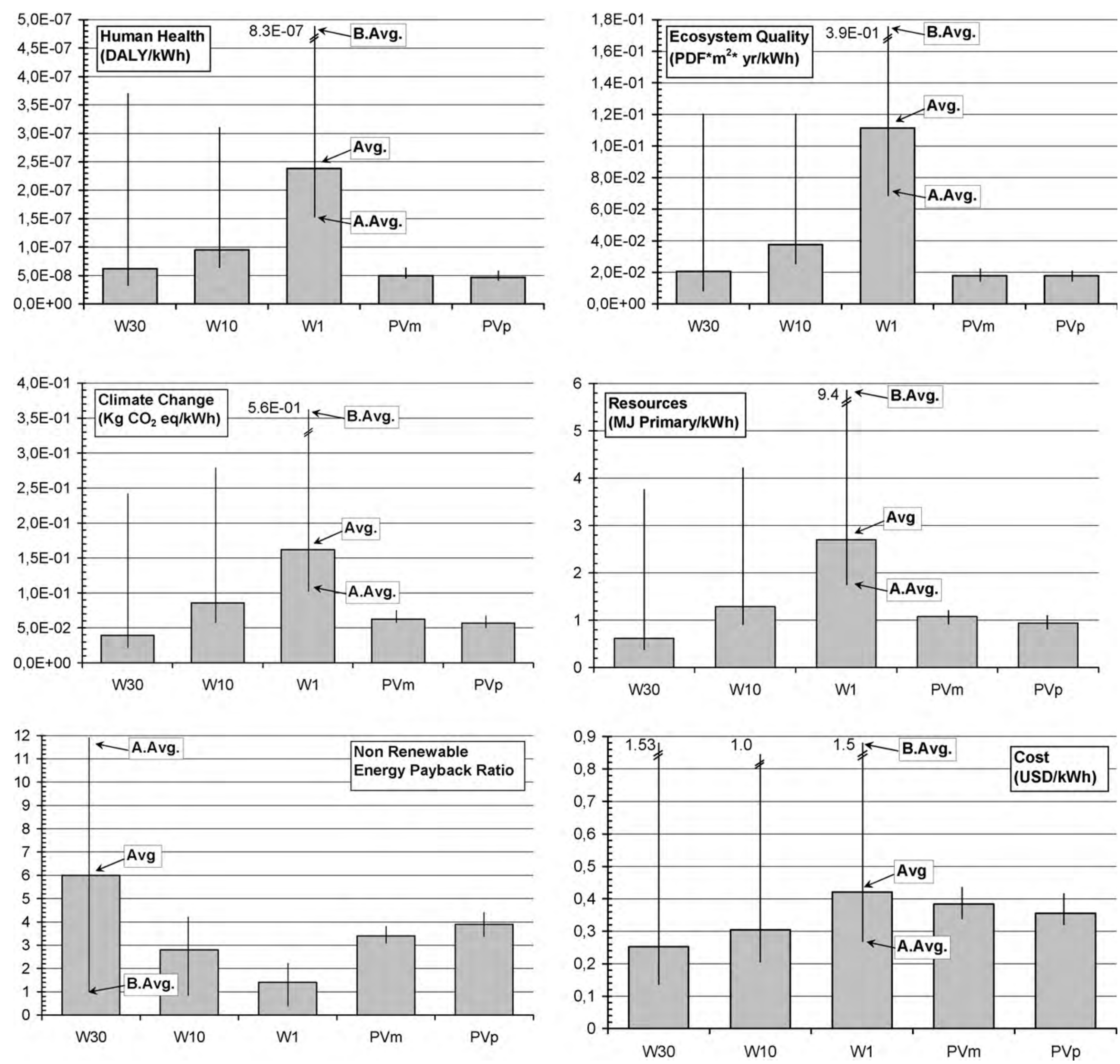

Fig. 3. Geographical dependence of the life cycle results (B.Avg.: below average; Avg.: average condition; A.Avg.: above average; W30: micro-wind 30 kW, W10: micro-wind 10 kW, W1: micro-wind 1 kW, PVm: 3 kWp mono-crystalline, PVp: 3 kWp poly-crystalline).

4. Centralized energy production comparison and results

The comparison between centralized energy production systems and distributed generation systems is a relevant step as it provides a better picture of distributed generation potential benefits for the Northeastern American context. Based on a recent LCA practitioner exchange [36], many comparison avenues are suggested, any of which can be assumed as correct. Indeed, practices helping to identify the possible affected conventional centralized energy production system remain to be improved [15]. There are two general approaches: the average approach, typically used in attributional LCA, and the marginal approach used in consequential LCA [15]. Sections 4.1 and 4.2 describe the average and the marginal approaches, respectively, while Section 4.3 presents the sensitivity analysis and the comparative results. All the results are discussed in Section 5.2.

4.1. Average approach

The average approach is based on the assumption that an increase in electricity supply from an alternative source on the grid will result in a drop in production from the centralized plants proportionally to their time-averaged contribution to the grid. The average approach could entail the use of the national or regional average data for the electricity production [14]. As the considered small-scale renewable technologies are in the Quebec province (Canada), a first option is to consider the Quebec centralized energy mix. Table 6 presents the power plants of the Quebec grid mix [37]. The average production cost is 0.049USD/kWh[1] [38]. This cost does not include the end-of-life cost. Since taking end-of-life costs into account would increase the final cost, the presented cost is considered coherent with the conservative approach. The national average could also consider the Canadian or the North American grid mixes instead. However, with a small net electricity importer or a net electricity exporter, it is more accurate to consider the regional average approach [39]. The province of Quebec is classified as a net electricity exporter [40].

The comparative results are presented in Section 4.3 and discussed in Section 5.2. Appendix A (Table 11) presents the life cycle performance of the Quebec grid mix based on generic data from the ecoinvent database.

4.2. Marginal approach

The average approach is considered as ideal but less realistic [4,7,13]. First, the centralized energy systems productions are not static as they respond to a variable energy demand. Second, renewable energy production systems are intermittent, and the exported energy to the grid varies in time. Therefore, a marginal approach is justified as it provides a better estimate of the actual consequences of using distributed generation (i.e. increase in electricity supply from an alternative source) [15].

The affected technologies (i.e. marginal) are here defined as the centralized energy systems affected by the small changes due to the energy supplied by small-scale renewable technologies. As the assessed systems lifetime is at least 20 years (Table 1), it is suggested to characterize the affected technologies over a short- and long-term period. A step-wise procedure proposed by Weidema was used in order to identify the affected technologies [41]. The procedure consists of determining the scale and time horizon of the studied change, the market delimitation and trend, the production constraints (i.e. technical, natural, political, market-related) and the technologies most sensitive to change. The logic is described in the following sections.

[1] Note that the current electricity acquisition cost in Quebec is 0.05 \$CDN/kWh (i.e. 0.049 USD with 2009 currency 1 CAD = 0.975 USD). A conservative approach was considered since the marginal cost of electricity in Quebec is 0.097 USD (0.10 \$CDN/kWh).

Table 6
Regional average data for the Quebec grid mix (production and import) [37].

Electrical generation plants	%
Coal and lignite	0.7
Oil	0.3
Natural gas	0.5
Nuclear	3.2
Hydropower	95.1
Wind power	0.2

4.2.1. Short-term marginal approach

The short-term affected technology (i.e. the short-term marginal technology) is defined as an existing technology changing its output due to small changes in electricity supply [41]. Before identifying the affected technologies, it is important to describe the situation in which change in electricity supply occurs. In case of a small increase in Quebec electricity consumption (e.g. for hot summer afternoons or cold winter days), the available power plant that will be used to produce this small amount of additional electricity is likely to be the oil power plant [42]. This is because, in practice, hydropower is limited to its present electricity production. As the increased demand for electricity cannot be covered by hydropower, it causes an increase in production from oil power plants. Then, we can assume that the energy supplied by small-scale renewable technologies will be able to cover at least a part of the increased Quebec electricity demand. The oil power plant will then change its output and could be identified as the affected technology.

As the energy supplied by small-scale renewable systems also occurs during non-peak consumption periods, the oil power plant is not the only affected centralized energy system. Hydropower will not change its output due to the small increase of electricity supply. In fact, hydropower is generally utilized to its maximum because of its very low production cost [43]. Therefore, more electricity will be available for export to the bordering market [40]. It was assumed that the most affected markets to a small change in electricity supply are those receiving a high percentage of total Quebec electricity exports which current trends [40] identify as New Brunswick (NB) and New York (NY) (95% of total Quebec exports to the US Northeast [44]). Appendix A (Fig. 4) shows the current and forecasted trends in Quebec electricity exports [40].

Before identifying the affected technologies in the identified markets, it is important to respectively describe their electricity situation. In case of a small increase in NB electricity consumption, the actual NB power plant that will be used to produce this additional electricity is also an oil power plant [45]. Therefore, as previously described, the energy supplied by small-scale renewable technologies will be able to cover at least a part of the increased NB electricity demand. The NB oil power plant will then change its output and could also be identified as the affected technology. Similar logic can be applied to the NY electricity market. In case of a small increase in NY electricity consumption, the actual power plants that will be used to produce this additional electricity are likely to be first the natural gas and second the oil power plant [46]. Therefore, the natural gas and oil power plant will change their output due to small changes in electricity supply and then could be identified as the affected technologies. The costs

Table 7
Five-step procedure results for the Northeastern American electricity market.

Proposed steps		Reference
Scale and time horizon of the studied change	Short to long	–
Market delimitation	Quebec, bordering provinces (New Brunswick and Ontario) and US Northeast	[40,44,49]
Market trend	Energy demand increasing	[40,48]
Production constraints (technical, natural, political, market-related)	Political: cap of CO_2 emissions could render the increase in natural gas and other fossil sources capacity more difficult – not considered in this study	[50]
Technologies most sensitive to change	*Short-term*: Oil (QC[a], US and NB) Natural gas (US)	[42,45,46]
	Long-term: Wind Power (QC) Hydropower (QC) Natural gas (US) Coal (US)	[40,48]

[a] Oil power plant is the short-term affected technology only during electricity consumption peaks (i.e. summer afternoons or cold winter days).

of the electricity produced by natural gas combustion turbines and oil are 0.08 and 0.14 USD/kWh[2], respectively [47].

4.2.2. Long-term marginal approach

The long-term affected technology (i.e. the long-term marginal technology) is defined as the technology installed or dismantled due to expected long-term changes in electricity supply [41]. The production volume and forecasts of the electricity demand do not suggest any decrease in the coming years, neither in the Quebec province, nor in any bordering markets [40,48]. In case of an increasing market, the affected technologies are those most likely to be installed (i.e. the unconstrained technologies with the lowest long-term production cost [41]).

In the province of Quebec, the technologies which have the potential to be the affected electricity sources by fulfilling the condition of being unconstrained are wind and hydropower [40]. These technologies should fulfill the long-term electricity demand increase. Therefore, in case of a small change in electricity supply due to the energy produced by small-scale renewable technology production, less hydro or wind Quebec electricity will be needed to make up for the increase: in other words, they represent the affected technologies. The technologies involved for large-scale electricity production are presented in Appendix A (Fig. 5).

The logic is similar for the bordering markets. Once again, it was assumed that the most affected markets by a small change in electricity supply are those receiving the higher percentage of total Quebec electricity exports. Referring to the forecasted share of total Quebec electricity exports [40], the US Northeast market is the one suspected to import a high percentage of the total long-term Quebec electricity exports. No information was available as to whether the New York market will remain the most sensitive. As for the long-term US electricity generation capacity additions by fuel types [48], the technologies which have the potential to be affected by fulfilling the condition of being unconstrained to the long-term increase of electricity demand are natural gas combustion turbines and coal. Therefore, in the case of small-scale renewable technology production, the energy supplied will be able to make up for the increase in electricity demand. Hence, less coal or natural gas electricity will be needed to compensate for the increase: in other words, coal and natural gas become the affected technology.

Uncertainty can arise from political constraints (i.e. future limits on GHG emissions) which could reduce the competitiveness of coal [48]. The forecasted costs of the electricity produced by hydro, wind and coal power plant are 0.1 USD/kWh while the forecasted costs of the electricity produced by natural gas combustion turbines is 0.08 USD/kWh [48]. The results of the step-wise procedure are summarized in Table 7. Section 4.3 presents the benefit analysis and the comparative results. As previously mentioned, all the results are discussed in Section 5.2. Appendix A (Table 11) presents the life cycle performance of the affected systems based on generic data from the ecoinvent database.

4.3. Benefit analysis and comparative results

This sections highlights when distributed generation can improve the life cycle performance of electricity production in a Northeastern American context. To do so, the affected centralized energy systems were compared to the selected small-scale renewable technologies. Thus, the centralized energy systems impacts were subtracted by those of the selected systems. The lower limit was defined by the most suitable technologies for the below average conditions (i.e. 3 kWp poly-crystalline) while the upper limit was determined using the most appropriate technologies for the above average conditions (i.e. micro-wind 30 kW). It is noteworthy to mention that for average conditions, the system's selection depends on the decision-maker preferences. However, the presented range itself remains the same from one decision-maker to another. When negative values are shown, no potential benefits are achieved, while positive values indicate an improvement over the affected system. Table 8 shows the benefit analysis results.

5. Discussion

5.1. Life cycle performance

This section discusses the obtained life cycle results (Sections 3.1 and 3.2). Fig. 2 shows the important contribution of the production phase for the small-scale renewable technologies. In fact, the contribution range is 50–95% depending on the environmental impact indicator (i.e. Human Health, Ecosystem Quality, Climate Change and Resources). The analysis of these percentages shows that material use dominates most environmental impacts [33]. The distribution and installation impacts contribution of micro-wind turbines is also significant as their percentage range from 45 to 15%. This is mainly due to the transportation phase to the installation site [11]. As described in Section 3.1, the transport average distance between the US manufacturer and the installation site (i.e. The province of Quebec) was estimated at 1500 km.

Fig. 3 shows that regardless of the environmental impact category, micro-wind turbines ranking remains the same. The same is true for the aquatic acidification and aquatic eutrophication impact categories which are not integrated as an endpoint category (Appendix A) (Table 9). A scaling down effect explains the dominance of micro-wind 30 kW on the assessed micro-wind

[2] All costs are stated in 2005 Canadian dollars. Conversion to US currency was made at a rate of 80 cents per Canadian dollar. A discount rate of 6% was also applied.

Table 8
Sensitivity analysis of distributed generation benefits (HH: Human Health; EQ: Ecosystem Quality; CC: Climate Change; RES: Resources; NR-EPR: Non-Renewable Energy Payback Ratio).

Approach	Affected systems	Selected systems	HH	EQ	CC	RES	NR-EPR	Cost[a]
			DALY	PDF*m^2*year	kg CO_2 $_{equiv.}$	MJ primary	–	USD
Average	Quebec grid mix	PVp@B.Avg[f]	−2.21E−08	6.65E−02	−2.93E−02	−3.55E−01	−2	−0.36
		W30@A.Avg[g]	6.92E−10	7.67E−02	1.62E−02	4.21E−01	7	−0.08
Short-term marginal	Oil[b]	PVp@B.Avg.	3.2E−07	7.4E−02	1.0E+00	1.5E+01	3	−0.27
		W30@A.Avg.	3.4E−07	8.4E−02	1.1E+00	1.6E+01	12	0.01
	Natural gas[c]	PVp@B.Avg.	−1.31E−08	−1.32E−02	1.75E−01	3.32E+00	3	−0.33
		W30@A.Avg.	9.69E−09	−3.01E−03	2.20E−01	4.09E+00	12	−0.05
Long-term marginal	Wind power[d]	PVp@B.Avg.	−3.81E−08	−1.45E−02	−5.33E−02	−8.95E−01	−16	−0.31
		W30@A.Avg.	−1.53E−08	−4.31E−03	−7.84E−03	−1.19E−01	−8	−0.03
	Hydropower[d]	PVp@B.Avg	−5.01E−08	−1.98E−02	−6.06E−02	−1.04E+00	−71	−0.31
		W30@A.Avg.	−2.73E−08	−9.64E−03	−1.51E−02	−2.60E−01	−62	−0.03
	Coal[e]	PVp@B.Avg.	1.66E−07	−4.58E−04	3.05E−01	3.42E+00	3	−0.31
		W30@A.Avg.	1.89E−07	9.69E−03	3.50E−01	4.19E+00	12	−0.03
	Natural gas[e]	PVp@B.Avg.	−1.31E−08	−1.32E−02	1.75E−01	3.32E+00	3	−0.33
		W30@A.Avg.	9.69E−09	−3.01E−03	2.20E−01	4.09E+00	12	−0.05

[a] Excludes end-of-life cost (conservative approach is considered).
[b] Represents the Quebec, New Brunswick and New York short-term affected technology.
[c] Represents the New York short-term affected technology.
[d] Represents the Quebec long-term affected technologies.
[e] Represents the US long-term affected technology.
[f] 3 kWp poly-crystalline for below average condition is the best technology (i.e. pessimistic scenario).
[g] Micro-wind 30 kW for above average condition is the best technology (i.e. optimistic scenario).

systems. This effect is explained with an increase in impact results and a decrease in produced energy [11]. In a less pronounced way, a dominance of poly-crystalline photovoltaic system is also observed on the assessed photovoltaic systems. A maximum difference of 25% can be observed between the mono-crystalline and poly-crystalline photovoltaic systems due to the small difference in produced energy between the two types of panel [1,33]. The highest contribution of environmental impacts is due to the respiratory effects caused by air emissions and the use of fossil energy resources [33].

In addition, Fig. 3 shows that the NR-EPR range is 0.4–11.9 for micro-wind and 3–4.4 for the photovoltaic system. These results show that investigated technologies have a good energy performance and that overall, micro-wind turbines could present a better efficiency [51]. However, for below average conditions, micro-wind turbines are energy intensive (i.e. NR-EPR values below 1). This clearly illustrates the technical feasibility limitations [4]. Therefore, the average wind speed for the selected sites should not be below 5.6 m/s. Finally, the scaling down effect still applies even for the energy aspect.

Table 4 provides the cost contribution of the investigated life cycle stages. It is interesting to note that the production stage of the studied systems remains dominant. Indeed, its contribution varies from 58% for micro-wind turbines to 76% for photovoltaic systems. This is explained by the high acquisition cost of the small-scale renewable systems [51,52]. Installation cost contribution remains second but does not exceed 20%. Once again, a scaling down effect can also be observed for the economic analysis (Fig. 3). This is also explained by the low energy produced in comparison to the higher total cost.

Table 5 presents the most favorable alternatives from an economic, environmental and energy standpoint (Section 3.3). For above average conditions, micro-wind 30 kW shows a win–win situation for the life cycle performance results. On the other hand, 3 kWp poly-crystalline is the most promising alternative for below average conditions. These results clearly indicate that the life cycle system performances are very sensitive to climatic conditions (i.e. geographic location). As presented in Table 5, for the different scenarios selection, the life cycle impact results per kWh ranges are as follows: Human Health: 3.1E−08 to 5.4E−08 DALY; Ecosystem Quality: 1E−02 to 2E−02 PDF*m^2*year; Climate Change: 2E−02 to 6.5E−02 kg CO_2 equiv.; Resources: 3.1E−01 to 1.1 MJ primary; NR-EPR: 11.9–3.4; Energy Cost: 0.13–0.41 USD. The upper limit was determined by the most suitable technologies for the above average conditions (i.e. micro-wind 30 kW) and the lower limit was defined by the most promising technologies for the below average conditions (i.e. 3 kWp poly-crystalline). Table 5 does not present the remaining systems (i.e. micro-wind 10 kW, micro-wind 1 kW and 3 kWp mono-crystalline) because of their low life cycle performance in comparison to the selected systems (i.e. material and energy inputs intensities in comparison to their produced energy). Also, as previously mentioned, for average conditions, the system's selection depends on the decision-maker preferences. However, the presented range itself remains the same from one decision-maker to another.

5.2. Potential benefits of distributed generation as an energy policy

One of the main applications of this study's results is to inform different stakeholders of the potential benefits and limitations of distributed generation to achieve today's energy policy goals. To meet this objective, the selected small-scale technologies were compared to the affected centralized energy systems (Sections 4.1 and 4.2). Table 8 shows the benefit analysis results. The following observations can be highlighted.

First, electricity production potential from small-scale renewable technologies does not show a potential benefit in comparison to the centralized Quebec grid mix due to the high percentage of hydropower energy system. Therefore, the specificities of the Quebec electricity mix make it difficult to justify renewable distributed generation [38]. However, referring to the scaling down effect, it can be observed, following an average approach, that producing renewable energy using wind turbines with a power rate higher than 30 kW could present interesting benefits even if it displaces electricity produced with a high percentage of hydropower. Second, renewable production using distributed generation, and more precisely micro-wind 30 kW, shows a potential benefit when oil centralized power system is affected (i.e. short-term marginal technology). Photovoltaic systems could also become a competitive alternative in case of a decrease in acquisition cost [53]. The third observation concerns the long-term perspective. Table 8 shows that using distributed generation, and more precisely micro-wind 30 kW, could improve the life cycle

performance of electricity production only if it has the potential to substitute coal energy production. Once again, photovoltaic systems could also become a competitive long-term alternative as acquisition cost is expected to decrease [53].

Even if the simultaneous use of different life cycle methods is often suggested [54], a conservative approach was applied in this paper mainly because of a lack of data. Therefore, improvements could be performed. For example, to remain consistent [34], it is recommended to include the end-of-life cost of the affected centralized energy system as all the assessment was performed on a cradle to grave basis. As distributed energy is close to the consumer, the transportation cost would be reduced. Thus, its inclusion in the final cost is also recommended. Hence, it is expected that the economic impact of the affected centralized energy systems should be higher than those presented. From an environmental point of view, the recycling processes during the end-of-life stage were not integrated in the assessed systems' boundaries. Their integration could decrease the environmental impacts for the small-scale renewable systems. In addition, the electricity transportation network between the centralized energy systems and the final user were not taken into account. Therefore, actual environmental impacts for the affected centralized energy systems are expected to be higher.

6. *Conclusions*

It can be stated that distributed generation can have the potential to improve the life cycle performance of electricity production in a Northeastern American context. However, this will depend on both the geographical locations of the small-scale renewable technologies and on the affected centralized electricity production. First, it has been shown that the life cycle system performances are very sensitive to climatic conditions (i.e. geographic location): micro-wind 30 kW was selected for above average condition while 3 kWp poly-crystalline was selected for below average condition. Second, production potential using distributed generation does not show a potential benefit in comparison to the centralized Quebec grid mix (i.e. average scenario). However, and this is the third main result, the assessed technologies, and more precisely micro-wind 30 kW, show potential benefits as long as oil and coal centralized technologies are affected (i.e. short and long-term marginal scenarios, respectively). Photovoltaic systems could also become competitive if their acquisition cost decreases. These results are the key to assess the extent to which distributed generation can reduce the use of the centralized electricity production. The present study does not provide hourly or seasonal energy production. Changes in time for the renewable energy production are fundamental and ignoring these could reduce the relevance of the study results. This is also the case for the affected centralized power systems as they can change at least twice a day. Future work will include an in-depth analysis of the actual displaced electricity production considering its dynamic patterns.

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Appendix A

Tables 9–11 and Figs. 4 and 5.

Table 9
Geographical dependence of the life cycle environmental impacts (IMPACT 2002+ midpoint categories; B.Avg.: below average; Avg.: average condition, A.Avg.: above average).

Impact category	Unit	Micro-wind 30 kW			Micro-wind 10 kW			Micro-wind 1 kW		
		B.Avg.	Avg.	A.Avg.	B.Avg.	Avg.	A.Avg.	B.Avg.	Avg.	A.Avg.
Carcinogens	kg C_2H_3Cl equiv.	1.2E−02	1.9E−03	9.7E−04	5.2E−03	1.6E−03	1.1E−03	2.0E−02	5.7E−03	3.7E−03
Non-carcinogens	kg C_2H_3Cl equiv.	3.5E−02	5.8E−03	2.9E−03	8.6E−03	2.6E−03	1.8E−03	3.9E−02	1.1E−02	7.1E−03
Respiratory inorganics	kg $PM_{2.5}$ equiv.	3.5E−04	5.8E−05	2.9E−05	3.9E−04	1.2E−04	8.0E−05	9.5E−04	2.7E−04	1.7E−04
Ionizing radiation	Bq C-14 equiv.	2.0E+00	3.2E−01	1.6E−01	1.9E+00	5.8E−01	3.9E−01	7.6E+00	2.2E+00	1.4E+00
Ozone layer depletion	kg CFC-11 equiv.	2.3E−08	3.9E−09	1.9E−09	3.2E−08	9.9E−09	6.7E−09	4.8E−08	1.4E−08	8.8E−09
Respiratory organics	kg C_2H_4 equiv.	1.4E−04	2.4E−05	1.2E−05	1.9E−04	5.9E−05	4.0E−05	3.6E−04	1.0E−04	6.5E−05
Aquatic ecotoxicity	kg TEG water	2.8E+01	4.6E+00	2.3E+00	2.8E+01	8.4E+00	5.7E+00	1.1E+02	3.2E+01	2.1E+01
Terrestrial ecotoxicity	kg TEG soil	1.4E+01	2.3E+00	1.2E+00	1.3E+01	4.1E+00	2.8E+00	4.5E+01	1.3E+01	8.3E+00
Terrestrial acid/nutri	kg SO_2 equiv.	7.7E−03	1.3E−03	6.4E−04	1.0E−02	3.2E−03	2.1E−03	1.7E−02	5.0E−03	3.2E−03
Land occupation	m^2 org.arable	2.3E−03	3.8E−04	1.9E−04	5.1E−03	1.5E−03	1.0E−03	6.5E−03	1.9E−03	1.2E−03
Aquatic acidification	kg SO_2 equiv.	1.5E−03	2.4E−04	1.2E−04	1.7E−03	5.3E−04	3.6E−04	4.1E−03	1.2E−03	7.4E−04
Aquatic eutrophication	kg PO_4 P-lim	9.0E−06	1.5E−06	7.5E−07	1.3E−05	3.9E−06	2.6E−06	2.3E−05	6.7E−06	4.2E−06
Global warming	kg CO_2 equiv.	2.4E−01	4.0E−02	2.0E−02	2.8E−01	8.6E−02	5.8E−02	5.6E−01	1.6E−01	1.0E−01
Non-renewable energy	MJ primary	3.7E+00	6.1E−01	3.0E−01	4.2E+00	1.3E+00	8.7E−01	9.2E+00	2.6E+00	1.7E+00
Mineral extraction	MJ surplus	6.2E−02	1.0E−02	5.2E−03	3.0E−02	8.9E−03	6.1E−03	2.3E−01	6.6E−02	4.2E−02

Impact category	Unit	3 kWp mono-crystalline			3 kWp poly-crystalline		
		B.Avg.	Avg.	A.Avg.	B.Avg.	Avg.	A.Avg.
Carcinogens	kg C_2H_3Cl equiv.	1.5E−03	1.3E−03	1.1E−03	1.5E−03	1.3E−03	1.2E−03
Non-carcinogens	kg C_2H_3Cl equiv.	3.3E−03	2.9E−03	2.5E−03	3.3E−03	2.8E−03	2.5E−03
Respiratory inorganics	kg $PM_{2.5}$ equiv.	6.2E−05	5.4E−05	4.8E−05	5.8E−05	5.0E−05	4.4E−05
Ionizing radiation	Bq C-14 equiv.	2.4E+00	2.1E+00	1.9E+00	1.6E+00	1.4E+00	1.3E+00
Ozone layer depletion	kg CFC-11 equiv.	1.4E−08	1.2E−08	1.1E−08	1.4E−08	1.2E−08	1.1E−08
Respiratory organics	kg C_2H_4 equiv.	5.1E−05	4.4E−05	3.9E−05	5.3E−05	4.6E−05	4.1E−05
Aquatic ecotoxicity	kg TEG water	9.6E+00	8.3E+00	7.4E+00	9.3E+00	8.1E+00	7.1E+00
Terrestrial ecotoxicity	kg TEG soil	2.3E+00	2.0E+00	1.8E+00	2.3E+00	2.0E+00	1.8E+00
Terrestrial acid/nutri	kg SO_2 equiv.	1.3E−03	1.1E−03	9.8E−04	1.2E−03	1.0E−03	9.3E−04
Land occupation	m^2 org.arable	5.6E−04	4.9E−04	4.3E−04	5.7E−04	4.9E−04	4.4E−04
Aquatic acidification	kg SO_2 equiv.	3.5E−04	3.1E−04	2.7E−04	3.2E−04	2.8E−04	2.5E−04
Aquatic eutrophication	kg PO_4 P-lim	6.1E−06	5.3E−06	4.7E−06	5.5E−06	4.8E−06	4.2E−06

Table 9 (*Continued*)

Impact category	Unit	3 kWp mono-crystalline			3 kWp poly-crystalline		
		B.Avg.	Avg.	A.Avg.	B.Avg.	Avg.	A.Avg.
Global warming	kg CO_2 equiv.	7.2E−02	6.3E−02	5.6E−02	6.5E−02	5.7E−02	5.0E−02
Non-renewable energy	MJ primary	1.2E+00	1.1E+00	9.5E−01	1.1E+00	9.4E−01	8.3E−01
Mineral extraction	MJ surplus	5.2E−03	4.5E−03	4.0E−03	5.4E−03	4.7E−03	4.1E−03

Table 10
Geographical dependence of the life cycle system performances (B.Avg.: below average; Avg.: average condition, A.Avg.: above average).

Systems	Conditions	Environmental performance (damage category)				Energy performance	Economic performance
		Human health	Ecosystem quality	Climate change	Resources	NR-EPR	Cost
		DALY	PDF*m^2*year	kg CO_2 equiv.	MJ primary	–	USD
Micro-wind 30 kW	B.Avg.	3.7E−07	1.2E−01	2.4E−01	3.7E+00	1	1.53
	Avg.	6.2E−08	2.1E−02	4.0E−02	6.2E−01	6	0.25
	A.Avg.	3.1E−08	1.0E−02	2.0E−02	3.1E−01	11.9	0.13
Micro-wind 10 kW	B.Avg.	3.1E−07	1.2E−01	2.8E−01	4.2E+00	0.9	1.01
	Avg.	9.5E−08	3.8E−02	8.6E−02	1.3E+00	2.8	0.30
	A.Avg.	6.4E−08	2.6E−02	5.8E−02	8.7E−01	4.2	0.20
Micro-wind 1 kW	B.Avg.	8.3E−07	3.9E−01	5.6E−01	9.4E+00	0.4	1.50
	Avg.	2.4E−07	1.1E−01	1.6E−01	2.7E+00	1.4	0.42
	A.Avg.	1.5E−07	7.1E−02	1.0E−01	1.7E+00	2.2	0.27
3 kWp Mono-crystalline	B.Avg.	5.7E−08	2.1E−02	7.2E−02	1.2E+00	3	0.44
	Avg.	5.0E−08	1.8E−02	6.3E−02	1.1E+00	3.4	0.38
	A.Avg.	4.4E−08	1.6E−02	5.6E−02	9.6E−01	3.8	0.34
3 kWp Poly-crystalline	B.Avg.	5.4E−08	2.0E−02	6.5E−02	1.1E+00	3.4	0.41
	Avg.	4.7E−08	1.8E−02	5.7E−02	9.4E−01	3.9	0.36
	A.Avg.	4.2E−08	1.6E−02	5.0E−02	8.4E−01	4.4	0.32

Table 11
Affected systems life cycle performance (HH: Human Health; EQ: Ecosystem Quality; CC: Climate Change; RES: Resources; NR-EPR: Non-Renewable Energy Payback Ratio).

Approach	Scenario	Affected systems	HH	EQ	CC	RES	NR-EPR	Cost[a]
			DALY	PDF*m^2*year	kg $CO_{2\ equiv.}$	MJ primary	–	USD
Average	1	Quebec grid mix	3.2E−08	8.7E−02	3.6E−02	7.3E−01	4.9	0.049
Short-term marginal	2–3–4	Oil[b]	3.7E−07	9.4E−02	1.1E+00	1.6E+01	0.2	0.14
	5	Natural gas[c]	4.1E−08	7.3E−03	2.4E−01	4.4E+00	0.3	0.08
Long-term marginal	6	Wind power[d]	1.6E−08	6.0E−03	1.2E−02	1.9E−01	19.6	0.1
	7	Hydropower[d]	4.0E−09	6.7E−04	4.7E−03	4.9E−02	74.2	0.1
	8	Coal[e]	2.2E−07	2.0E−02	3.7E−01	4.5E+00	0.3	0.1
	9	Natural gas[e]	4.1E−08	7.3E−03	2.4E−01	4.4E+00	0.3	0.08

[a] Excludes end-of-life cost (conservative approach is considered).
[b] Represents the Quebec, New Brunswick and New York short-term affected technology.
[c] Represents the New York short-term affected technology.
[d] Represents the Quebec long-term affected technologies.
[e] Represents the US long-term affected technology.

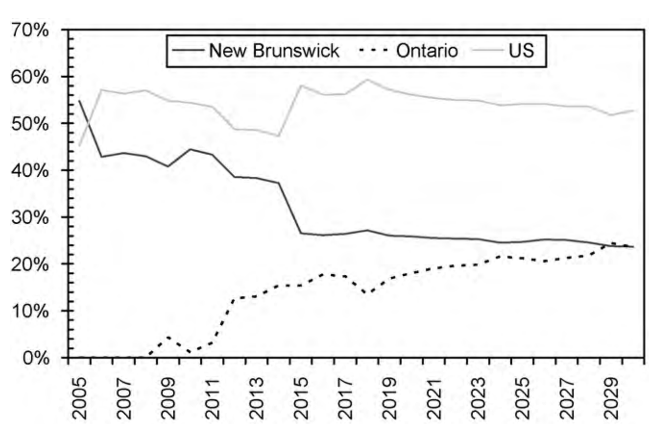

Fig. 4. Forecasted share of total exports among the three main Quebec electricity export markets (% of total exports) [40].

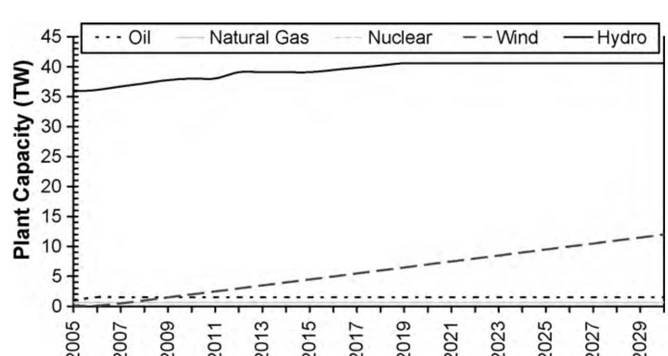

Fig. 5. Capacity trends by plant type for the Quebec province [40].

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